

High-Frequency QPOs as a Product of Inner Disk Dynamics around Neutron Stars

M. Hakan Erkut

Physics Department, İstanbul Kültür University, Ataköy Campus, Bakırköy 34156, İstanbul, Turkey

Abstract. The kHz QPOs observed in a neutron star low mass X-ray binary are likely to be produced in the innermost regions of accretion disk around the neutron star. The rotational dynamics of the inner disk can be characterized by the presence of either sub-Keplerian or super-Keplerian accretion flow depending on the relative fastness of the neutron spin as compared to the Keplerian frequency at the inner disk radius. Within the magnetosphere-disk interaction model, the frequency difference between the two kHz QPOs observed in a given source can be estimated to be slightly higher than or nearly around the neutron star spin frequency if the neutron star is a slow rotator and less than the stellar spin frequency if the neutron star is a fast rotator.

Keywords: Accretion and accretion disks, Oscillations, Neutron stars, X-ray binaries

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INTRODUCTION

The observations of neutron stars in low mass X-ray binaries (LMXBs) led to the discovery of the kHz quasi-periodic oscillations (QPOs) and the burst oscillations [8]. It has almost been firmly established from the observations that the frequency of the burst oscillation is very close to the spin frequency of the neutron star, i.e., $\nu_{\text{burst}} \simeq \nu_{\text{spin}}$ [5].

The kHz QPOs from neutron star LMXBs have some important observational properties. These high-frequency QPOs usually appear in pairs in the $\simeq 200 - 1200$ Hz range. Both the upper kHz QPO frequency ν_2 and the lower kHz QPO frequency ν_1 correlate with the X-ray luminosity of the source [8]. According to early observations, the peak separation between the kHz QPO frequencies seemed to be directly related to the spin frequency of the neutron star, i.e., $\Delta\nu = \nu_2 - \nu_1 \simeq \nu_{\text{burst}} \simeq \nu_{\text{spin}}$. The systematic analysis of all QPO data, however, showed that the peak separation $\Delta\nu$ is not constant for a given source. Indeed, $\Delta\nu$ decreases as both the kHz QPO frequencies ν_2 and ν_1 increase [6]. According to the analysis of the early kHz QPO data, $\Delta\nu \simeq \nu_{\text{burst}} \simeq \nu_{\text{spin}}$ for $\nu_{\text{spin}} < 400$ Hz and $\Delta\nu \simeq \nu_{\text{burst}}/2 \simeq \nu_{\text{spin}}/2$ for $\nu_{\text{spin}} \gtrsim 400$ Hz among neutron star sources with different burst or spin frequencies [9]. The recent analysis of all available data, however, revealed that $\Delta\nu$ significantly deviates from either ν_{spin} or $\nu_{\text{spin}}/2$ for almost half of all sources and that $\Delta\nu/\nu_{\text{spin}}$ decreases from a value > 1 to a value $< 1/2$ as ν_{spin} increases [5].

The frequency correlations of kHz QPOs can be explained, albeit qualitatively at this stage, within the boundary region model [1, 4]. Next, we discuss the interpretation of the observational properties of kHz QPOs within the boundary region model.

BOUNDARY REGION MODEL

According to the boundary region model (BRM), the likely origin of the high-frequency QPOs is the innermost region of the accretion disk around the compact object. In neutron star sources, the kHz QPOs are produced in the boundary region (BR) or the boundary layer where the angular velocity of the accretion flow is non-Keplerian [1, 4]. In black hole candidates, it is the relativistic disk region near the innermost stable circular orbit which is responsible for the production of the high-frequency QPO pairs with a frequency ratio around 1.5 [2].

The interaction of the inner disk with the magnetosphere of the neutron star rotating with an angular frequency $\Omega_{\text{spin}} = \Omega_*$ leads to the formation of a magnetohydrodynamic BR throughout which the angular frequency Ω of the accreting matter deviates from the Keplerian frequency Ω_K to match the stellar spin frequency Ω_* at the innermost disk radius r_{in} [3].

In the conventional regime of accretion where the neutron star is a *slow rotator*, $\Omega_* < \Omega_K(r_{\text{in}})$ and the angular frequency profile of the matter is characterized by a maximum frequency $\Omega_{\text{max}} = \Omega(r_0)$ at some radius r_0 in the BR [3]. In the Newtonian regime, the radial epicyclic frequency κ is the same as the angular frequency Ω if $\Omega = \Omega_K$. It is a well known fact that the nondegeneracy between κ and Ω appears in the regime of strong gravity due to general relativistic effects. Even in the non-relativistic regime, the degeneracy between κ and Ω is removed in a hydrodynamic BR throughout which $\kappa > \Omega$ if the BR is sub-Keplerian [1, 4]. The analysis of global hydrodynamic modes of free oscillations in a typical sub-Keplerian BR revealed that the fastest growing modes are excited near the disk radius r_0 where Ω is maximum. The frequencies of the growing hydrodynamic modes match the test-particle frequency branches $\kappa \pm \Omega$ and κ in the limit of small hydrodynamic corrections. The same modes grow in the $\simeq r_{\text{in}} - r_0$ range. The difference between the two consecutive frequency bands of the growing modes is $\sim \Omega$ which corresponds to the frequency separations $\Delta\omega \simeq \Omega_{\text{max}} \simeq 1.2 - 1.3\Omega_*$ and $\Delta\omega \simeq \Omega_*$ at $r = r_0$ and $r = r_{\text{in}}$, respectively [4]. Note that the estimations of the BRM for the peak separation of the growing mode frequencies are in agreement with the distribution of the $\Delta\nu/\nu_{\text{spin}}$ values observed for the relatively slowly rotating neutron stars with spin frequencies below ~ 400 Hz [5]. The frequencies of the modes which grow in amplitude at any particular radius in the BR increase all together as the local sound speed c_s increases [4]. The magnetic field strengths of neutron stars in LMXBs are generally thought to be weak enough for the radiation pressure to be important in the innermost disk regions. For a radiation pressure dominated inner disk, $c_s \propto \dot{M}$, where \dot{M} is the mass inflow rate in the inner disk [7]. We expect, in accordance with the correlations of the kHz QPO frequencies, that the growing mode frequencies correlate with the X-ray luminosity $L_X \propto \dot{M}$. Figure 1 exhibits the correlation between the frequencies ν_1 and ν_2 of two consecutive modes growing at the innermost disk radius r_{in} and the correlation between the frequency difference $\Delta\nu = \nu_2 - \nu_1$ and the upper mode frequency ν_2 of the same modes estimated by the BRM [4] for a putative neutron star with a spin frequency 300 Hz. Note from Figure 1 that the power-law fit to the kHz QPO data of Sco X-1 [6] can also be used to fit the sample data estimated by the BRM simply by adjusting the proportionality constant in the power law.

According to the present distribution of $\Delta\nu/\nu_{\text{spin}}$ over ν_{spin} [5], the relatively fast

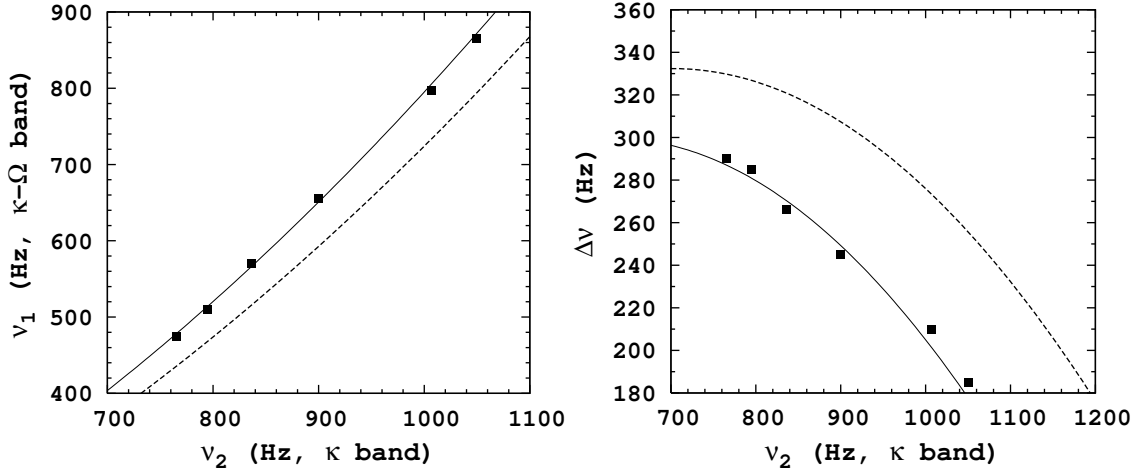


FIGURE 1. Power-law fits to the correlation of the frequencies ν_1 and ν_2 and to the correlation between the frequency difference $\Delta\nu$ and ν_2 estimated by the BRM for the growing modes at the innermost disk radius. The power law is given by $\nu_1 = C(\nu_2/1000)^{1.9}$ Hz, where $C = 795$ for the solid curve and $C = 724$ for the dashed curve [6].

rotating neutron stars with $\nu_{\text{spin}} \gtrsim 400$ Hz seem to exhibit kHz QPO pairs for which $\Delta\nu$ is around or sometimes even less than $\nu_{\text{spin}}/2$. The systematic trend of observing small values of $\Delta\nu/\nu_{\text{spin}}$ for sufficiently high values of ν_{spin} could be the result of a change in the structure of the BR. In the magnetosphere-disk interaction model, the structure of the BR depends on the fastness parameter, $\omega_* = \Omega_*/\Omega_K(r_{\text{in}})$. The neutron star is a *slow rotator* if $\omega_* < 1$. For a *slow rotator*, the BR is sub-Keplerian as mentioned above. In the accretion regime where the neutron star is a *fast rotator* ($\omega_* \geq 1$), we expect to find a super-Keplerian BR for $r_{\text{in}} \leq r \leq r_A$, where r_A is the effective magnetic coupling radius, e.g., the Alfvén radius. The magnetic coupling radius, for a *fast rotator*, exceeds the corotation radius r_{co} , where $\Omega_* = \Omega_K$. The angular frequency Ω of the disk matter accreting through the super-Keplerian BR deviates from the Keplerian frequency Ω_K to match the stellar spin frequency Ω_* at $r = r_{\text{in}}$. Condition for the *fast rotator* to be an accreting neutron star and not to be a propeller can be written as $\Omega_K \leq \Omega \leq \sqrt{2}\Omega_K$ for $r_{\text{in}} \leq r \leq r_A$. Thus, a *fast rotator* accretes only within a limited range of the fastness, i.e., $1 \leq \omega_* \leq \sqrt{2}$. In Figure 2, we display the run of the dynamical frequencies κ (dashed curve) and Ω (dotted curve) throughout the super-Keplerian BR for a *fast rotator* with $\omega_* = 1.4$. The angular frequency Ω lies in the $\Omega_K - \sqrt{2}\Omega_K$ range (region bounded by the solid curves) as expected. The radial epicyclic frequency κ is always less than Ω_* and sometimes even less than $\Omega_*/2$. As compared to the right panel of Figure 2, r_A has a greater value in the left panel. Note that $\kappa(r_{\text{in}})$ decreases as r_A decreases. Although the mode analysis is necessary to distinguish among different hydrodynamic modes, it is noteworthy to find the frequency separation of two consecutive modes to be $\Delta\omega \simeq \kappa$ if the high-frequency modes with $\Omega \pm \kappa$ and Ω branches determine the kHz QPOs in the *fast rotator* regime. For the *fast rotators*, $\Delta\omega$ decreases as \dot{M} increases since $r_A \propto \dot{M}^{-2/7}$ for the Alfvén radius.

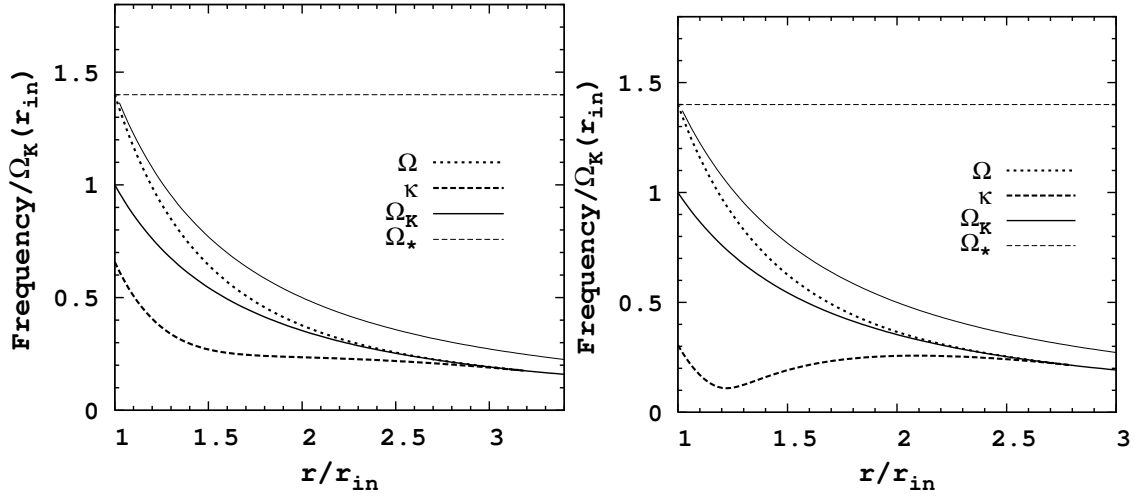


FIGURE 2. The radial profiles of the dynamical frequencies κ (dashed curve) and Ω (dotted curve) in the BR of the accretion disk around a rapidly rotating neutron star with a fastness $\omega_* = 1.4$. The two solid curves correspond to the frequencies Ω_K and $\sqrt{2}\Omega_K$.

CONCLUSIONS

The BRM estimations for the peak separations and correlations of kHz QPOs are in agreement with observations. A sub-Keplerian BR is appropriate for the *slow rotators* that exhibit kHz QPOs with the peak separations that are slightly higher than or nearly around or slightly less than the neutron star spin frequency. Within the magnetosphere-disk interaction model, super-Keplerian BRs are more appropriate for the accretion disks around *fast rotators*. In a super-Keplerian BR, the frequency difference of the mode branches is always less than the stellar spin frequency if the neutron star is a *fast rotator*.

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